

The $I^G J^{PC} = 0^+ 1^{-+}$ Tetraquark State

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We study the tetraquark state with $I^G J^{PC} = 0^+ 1^{-+}$ in the QCD sum rule. We exhaust all possible flavor structures by using a diquark-antidiquark construction and find that the flavor structure $(\bar{\mathbf{3}} \otimes \bar{\mathbf{6}}) \oplus (\mathbf{6} \otimes \mathbf{3})$ is preferred. There are altogether four independent currents which have the quark contents $qs\bar{q}\bar{s}$. By using both the Shifman-Vainshtein-Zakharov (SVZ) sum rule and the finite energy sum rule, these currents lead to mass estimates around 1.8–2.1 GeV, where the uncertainty is due to the mixing of two single currents. Its possible decay modes are S -wave $b_1(1235)\eta$ and $b_1(1235)\eta'$, and P -wave KK , $\eta\eta$, $\eta\eta'$ and $\eta'\eta'$, etc. The decay width is around 150 MeV through a rough estimation.

PACS numbers: 12.39.Mk, 11.40.-q, 12.38.Lg

Keywords: exotic mesons, tetraquark, QCD sum rule

Manifestly exotic hadron states which are not reached by three quarks for baryons and a quark-antiquark pair for mesons provide one of the most important subjects in hadron physics. The confirmation of their existence (or nonexistence) and the study of their structure are of great importance for the understanding of strong interaction dynamics at low energy [1].

Quantum numbers can tell whether a hadron is exotic or not. For instance baryons with strangeness $S = +1$ and mesons with $J^{PC} = 1^{-+}$ are such states. For the baryon sector, the pentaquark Θ^+ has been studied intensively since 2003 [2]. But the existence is still controversial. For the meson sector, the π_1 mesons of $I^G J^{PC} = 1^- 1^{-+}$ are listed as manifestly exotic states in the PDG for some time [3, 4, 5], and a lot of theoretical considerations have been made [6, 7]. So far, many of them are for the isovector $I = 1$ states. In principle, an isoscalar state is also possible, though not observed experimentally [7]. We have performed the QCD sum rule analyses of the light scalar mesons (σ , κ , f_0 and a_0), $Y(2175)$ and π_1 mesons [8, 9]. All our results are consistent with the experimental observations. Encouraged by this, we would like to extend the QCD sum rule analysis using tetraquark currents for these $I^G J^{PC} = 0^+ 1^{-+}$ states.

The QCD sum rule requires a computation of a two-point correlation function in the form of operator product expansion (OPE), which is then fitted by a phenomenological function to extract physical hadron properties [10]. To calculate the OPE, we need employ an interpolating field (current) which couples to the physical state we consider. For tetraquarks, there are several independent currents and it is important to establish how one or some of them should be chosen. We

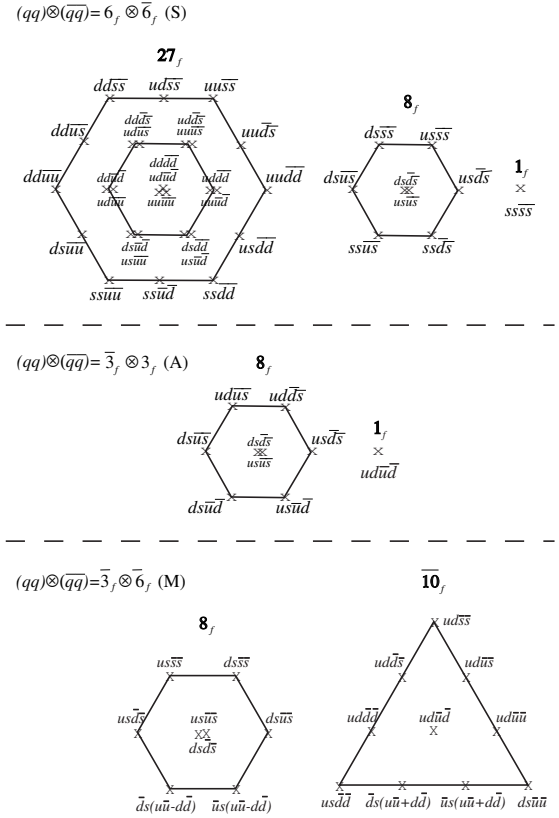


FIG. 1: Weight diagrams for $\mathbf{6}_f \otimes \bar{\mathbf{6}}_f(\mathbf{S})$ (top panel), $\bar{\mathbf{3}}_f \otimes \mathbf{3}_f(\mathbf{A})$ (middle panel), and $\bar{\mathbf{3}}_f \otimes \bar{\mathbf{6}}_f(\mathbf{M})$ (bottom panel). The weight diagram for $\mathbf{6}_f \otimes \mathbf{3}_f(\mathbf{M})$ is the charge-conjugation transformation of the bottom one.

have systematically performed the classification of currents by using the diquark-antidiquark $((qq)(\bar{q}\bar{q}))$ construction [8, 9]. The currents constructed from the quark-antiquark pairs $((\bar{q}q)(\bar{q}q))$ can be written as a combination of these $((qq)(\bar{q}\bar{q}))$ currents. We note here that the mixing can happen between hybrid states, tetraquark

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states, and even six-quark states, while the currents can also couple to all these states. However, it always makes sense to clarify what a single channel problem tells us before entering more sophisticated coupled channel problems. Therefore, here we concentrate exclusively on the tetraquark properties with some details.

The tetraquark currents with the quantum numbers $J^{PC} = 1^{-+}$ have been constructed in our previous paper [9]. Now we need construct the isoscalar ones. The flavor structures are shown in Fig. 1 in terms of $SU(3)$ weight diagrams. The ideal mixing scheme is used since it is expected to work well for hadrons except for the pseudoscalar mesons. In order to have a definite charge-conjugation parity, the diquark and antidiquark inside can have the same flavor symmetry, which is either symmetric $\mathbf{6}_f \otimes \bar{\mathbf{6}}_f$ (**S**) or antisymmetric $\bar{\mathbf{3}}_f \otimes \mathbf{3}_f$ (**A**). Another option is the combination of $\bar{\mathbf{3}}_f \otimes \bar{\mathbf{6}}_f$ and $\mathbf{6}_f \otimes \mathbf{3}_f$ (**M**), which can also have a definite charge-conjugation parity.

From Fig. 1, we find that there are altogether six isospin singlets:

$$\begin{aligned} qq\bar{q}\bar{q}(\mathbf{S}), qs\bar{q}\bar{s}(\mathbf{S}), ss\bar{s}\bar{s}(\mathbf{S}) &\sim \mathbf{6}_f \otimes \bar{\mathbf{6}}_f \quad (\mathbf{S}), \\ qq\bar{q}\bar{q}(\mathbf{A}), qs\bar{q}\bar{s}(\mathbf{A}) &\sim \bar{\mathbf{3}}_f \otimes \mathbf{3}_f \quad (\mathbf{A}), \\ qs\bar{q}\bar{s}(\mathbf{M}) &\sim (\bar{\mathbf{3}}_f \otimes \bar{\mathbf{6}}_f) \oplus (\mathbf{6}_f \otimes \mathbf{3}_f) \quad (\mathbf{M}), \end{aligned} \quad (1)$$

where q represents an *up* or *down* quark, and s represents a *strange* quark. For each state, there are several independent currents. We list them in the following.

1. For the three isospin singlets of $\mathbf{6}_f \otimes \bar{\mathbf{6}}_f$ (**S**):

$$\begin{aligned} \eta_{1\mu}^S &\sim u_a^T C \gamma_5 d_b (\bar{u}_a \gamma_\mu \gamma_5 C \bar{d}_b^T + \bar{u}_b \gamma_\mu \gamma_5 C \bar{d}_a^T) \\ &\quad + u_a^T C \gamma_\mu \gamma_5 d_b (\bar{u}_a \gamma_5 C \bar{d}_b^T + \bar{u}_b \gamma_5 C \bar{d}_a^T), \\ \eta_{2\mu}^S &\sim u_a^T C \gamma^\nu d_b (\bar{u}_a \sigma_{\mu\nu} C \bar{d}_b^T - \bar{u}_b \sigma_{\mu\nu} C \bar{d}_a^T) \\ &\quad + u_a^T C \sigma_{\mu\nu} d_b (\bar{u}_a \gamma^\nu C \bar{d}_b^T - \bar{u}_b \gamma^\nu C \bar{d}_a^T), \end{aligned} \quad (2)$$

$$\begin{aligned} \eta_{3\mu}^S &\sim u_a^T C \gamma_5 s_b (\bar{u}_a \gamma_\mu \gamma_5 C \bar{s}_b^T + \bar{u}_b \gamma_\mu \gamma_5 C \bar{s}_a^T) \\ &\quad + u_a^T C \gamma_\mu \gamma_5 s_b (\bar{u}_a \gamma_5 C \bar{s}_b^T + \bar{u}_b \gamma_5 C \bar{s}_a^T), \\ \eta_{4\mu}^S &\sim u_a^T C \gamma^\nu s_b (\bar{u}_a \sigma_{\mu\nu} C \bar{s}_b^T - \bar{u}_b \sigma_{\mu\nu} C \bar{s}_a^T) \\ &\quad + u_a^T C \sigma_{\mu\nu} s_b (\bar{u}_a \gamma^\nu C \bar{s}_b^T - \bar{u}_b \gamma^\nu C \bar{s}_a^T). \end{aligned} \quad (3)$$

$$\begin{aligned} \eta_{5\mu}^S &\sim s_a^T C \gamma_5 s_b (\bar{s}_a \gamma_\mu \gamma_5 C \bar{s}_b^T + \bar{s}_b \gamma_\mu \gamma_5 C \bar{s}_a^T) \\ &\quad + s_a^T C \gamma_\mu \gamma_5 s_b (\bar{s}_a \gamma_5 C \bar{s}_b^T + \bar{s}_b \gamma_5 C \bar{s}_a^T), \\ \eta_{6\mu}^S &\sim s_a^T C \gamma^\nu s_b (\bar{s}_a \sigma_{\mu\nu} C \bar{s}_b^T - \bar{s}_b \sigma_{\mu\nu} C \bar{s}_a^T) \\ &\quad + s_a^T C \sigma_{\mu\nu} s_b (\bar{s}_a \gamma^\nu C \bar{s}_b^T - \bar{s}_b \gamma^\nu C \bar{s}_a^T). \end{aligned} \quad (4)$$

where $\eta_{1\mu}^S$ and $\eta_{2\mu}^S$ are the two independent currents containing only light flavors; $\eta_{3\mu}^S$ and $\eta_{4\mu}^S$ are the two independent ones containing one $s\bar{s}$ pair; $\eta_{5\mu}^S$ and $\eta_{6\mu}^S$ are the two independent ones containing two $s\bar{s}$ pairs.

2. For the two isospin singlets of $\bar{\mathbf{3}}_f \otimes \mathbf{3}_f$ (**A**):

$$\begin{aligned} \eta_{1\mu}^A &\sim u_a^T C \gamma_5 d_b (\bar{u}_a \gamma_\mu \gamma_5 C \bar{d}_b^T - \bar{u}_b \gamma_\mu \gamma_5 C \bar{d}_a^T) \\ &\quad + u_a^T C \gamma_\mu \gamma_5 d_b (\bar{u}_a \gamma_5 C \bar{d}_b^T - \bar{u}_b \gamma_5 C \bar{d}_a^T), \\ \eta_{2\mu}^A &\sim u_a^T C \gamma^\nu d_b (\bar{u}_a \sigma_{\mu\nu} C \bar{d}_b^T + \bar{u}_b \sigma_{\mu\nu} C \bar{d}_a^T) \\ &\quad + u_a^T C \sigma_{\mu\nu} d_b (\bar{u}_a \gamma^\nu C \bar{d}_b^T + \bar{u}_b \gamma^\nu C \bar{d}_a^T), \end{aligned} \quad (5)$$

$$\begin{aligned} \eta_{3\mu}^A &\sim u_a^T C \gamma_5 s_b (\bar{u}_a \gamma_\mu \gamma_5 C \bar{s}_b^T - \bar{u}_b \gamma_\mu \gamma_5 C \bar{s}_a^T) \\ &\quad + u_a^T C \gamma_\mu \gamma_5 s_b (\bar{u}_a \gamma_5 C \bar{s}_b^T - \bar{u}_b \gamma_5 C \bar{s}_a^T), \\ \eta_{4\mu}^A &\sim u_a^T C \gamma^\nu s_b (\bar{u}_a \sigma_{\mu\nu} C \bar{s}_b^T + \bar{u}_b \sigma_{\mu\nu} C \bar{s}_a^T) \\ &\quad + u_a^T C \sigma_{\mu\nu} s_b (\bar{u}_a \gamma^\nu C \bar{s}_b^T + \bar{u}_b \gamma^\nu C \bar{s}_a^T), \end{aligned} \quad (6)$$

where $\eta_{1\mu}^A$ and $\eta_{2\mu}^A$ are the two independent currents containing only light flavors; $\eta_{3\mu}^A$ and $\eta_{4\mu}^A$ are the two independent ones containing one $s\bar{s}$ pair.

3. For the isospin singlet of $(\bar{\mathbf{3}}_f \otimes \bar{\mathbf{6}}_f) \oplus (\mathbf{6}_f \otimes \mathbf{3}_f)$ (**M**),

$$\begin{aligned} \eta_{1\mu}^M &\sim u_a^T C \gamma_\mu s_b (\bar{u}_a C \bar{s}_b^T + \bar{u}_b C \bar{s}_a^T) \\ &\quad + u_a^T C s_b (\bar{u}_a \gamma_\mu C \bar{s}_b^T + \bar{u}_b \gamma_\mu C \bar{s}_a^T), \\ \eta_{2\mu}^M &\sim u_a^T C \sigma_{\mu\nu} \gamma_5 s_b (\bar{u}_a \gamma^\nu \gamma_5 C \bar{s}_b^T + \bar{u}_b \gamma^\nu \gamma_5 C \bar{s}_a^T) \\ &\quad + u_a^T C \gamma^\nu \gamma_5 s_b (\bar{u}_a \sigma_{\mu\nu} \gamma_5 C \bar{s}_b^T + \bar{u}_b \sigma_{\mu\nu} \gamma_5 C \bar{s}_a^T), \\ \eta_{3\mu}^M &\sim u_a^T C s_b (\bar{u}_a \gamma_\mu C \bar{s}_b^T - \bar{u}_b \gamma_\mu C \bar{s}_a^T) \\ &\quad + u_a^T C \gamma_\mu s_b (\bar{u}_a C \bar{s}_b^T - \bar{u}_b C \bar{s}_a^T), \\ \eta_{4\mu}^M &\sim u_a^T C \gamma^\nu \gamma_5 s_b (\bar{u}_a \sigma_{\mu\nu} \gamma_5 C \bar{s}_b^T - \bar{u}_b \sigma_{\mu\nu} \gamma_5 C \bar{s}_a^T) \\ &\quad + u_a^T C \sigma_{\mu\nu} \gamma_5 s_b (\bar{u}_a \gamma^\nu \gamma_5 C \bar{s}_b^T - \bar{u}_b \gamma^\nu \gamma_5 C \bar{s}_a^T), \end{aligned} \quad (7)$$

where $\eta_{i\mu}^M$ are the four independent ones containing one $s\bar{s}$ pair. The above structure has some implications on their decay patterns.

The expressions of Eqs. (2)-(7) are not exactly correct, since they do not have a definite isospin. For instance, the current $\eta_{3\mu}^A$ should contain $(us\bar{u}\bar{s} + ds\bar{d}\bar{s})$ in order to have $I = 0$. However, in the following QCD sum rule analysis, we find that there is no difference between these two cases in the limit that the masses and condensates of the *up* and *down* quarks are the same. Actually we also ignore a small quark mass effect ($m_u \sim m_d \lesssim 10$ MeV).

By using these tetraquark currents, we have performed the OPE calculation up to dimension 12. Values for various condensates and m_s follow the references [3, 11]. There are altogether 14 currents. It turns out that some of them lead to the same results of OPEs as the previous ones in Ref. [9]: $\eta_{1,2,3,4\mu}^S \sim \eta_{1,2,3,4\mu}^S$ [9], $\eta_{3,4\mu}^A \sim \eta_{1,2\mu}^A$ [9], and $\eta_{1,2,3,4\mu}^M \sim \eta_{5,6,7,8\mu}^M$ [9]. Therefore, we just need calculate the OPEs of $\eta_{5,6\mu}^S$ and $\eta_{1,2\mu}^A$. The full OPE expressions are too lengthy and are omitted here.

In our previous paper [9] we have found that the OPEs of the currents $\eta_{i\mu}^S$'s and $\eta_{i\mu}^A$'s lead to unphysical results where the spectral densities $\rho(s)$ become negative in the region of $2 \text{ GeV}^2 \lesssim s \lesssim 4 \text{ GeV}^2$. We find this to be the case also for the isoscalar currents. Therefore, our QCD sum rule analysis does not support a tetraquark state which has a flavor structure either $\mathbf{6}_f \otimes \bar{\mathbf{6}}_f$ or $\bar{\mathbf{3}}_f \otimes \mathbf{3}_f$ and a mass less than 2 GeV.

We shall discuss only the currents of the mixed flavor symmetry. We find there is only one set of four independent currents as given in Eqs. (7), unlike the isovector

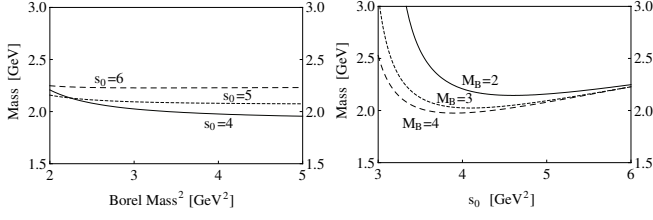


FIG. 2: The mass of the state $qs\bar{q}\bar{s}$ calculated by using the current $\eta_{2\mu}^M$, as functions of M_B^2 (left) and s_0 (right) in units of GeV.

case which have two sets. The spectral densities calculated by the mixed currents are positive for a wide range of s , and the convergence of OPE is very good in the region of $2 \text{ GeV}^2 < M_B^2 < 5 \text{ GeV}^2$ as in our previous study [9]. In general, the pole contribution should be large enough in the SVZ sum rule. However, the pole contributions of multiquark states are rather small due to the large continuum contribution. Therefore a careful choice of the threshold parameter is important in order to subtract the continuum contribution.

When using the SVZ sum rule, the mass is obtained as functions of Borel mass M_B and threshold value s_0 . As an example, we show the mass calculated from currents $\eta_{2\mu}^M$ in Fig. 2. The Borel mass dependence is weak, as shown in the upper figure; the s_0 dependence has a minimum where the stability is the best, as shown in the bottom figure. The minimum is around 2.0 GeV, which we choose to be our prediction. The other three independent currents $\eta_{1\mu}^M$, $\eta_{3\mu}^M$ and $\eta_{4\mu}^M$ lead to similar results, which are around 2.1 GeV, 1.9 GeV and 2.0 GeV respectively.

When using the finite energy sum rule, the mass is obtained as a function of the threshold value s_0 , which is shown in Fig. 3. There is also a mass minimum around 2.1 GeV, 1.9 GeV, 1.9 GeV and 2.0 GeV for currents $\eta_{1\mu}^M$, $\eta_{2\mu}^M$, $\eta_{3\mu}^M$ and $\eta_{4\mu}^M$ respectively. In a short summary, we have performed a QCD sum rule analysis for $qs\bar{q}\bar{s}$. The mass obtained is around 2.0 GeV. We label this state $\sigma_1(2000)$.

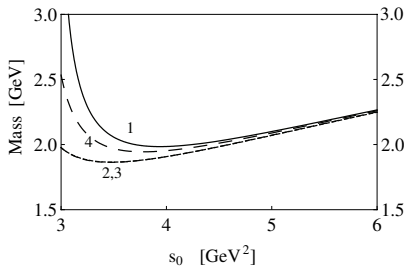


FIG. 3: The mass calculated using the finite energy sum rule. The labels besides the lines indicate the suffix i of the current $\eta_{i\mu}^M$ ($i = 1, \dots, 4$).

We can also study the mixing of these four currents.

The currents $\eta_{1\mu}^M$ and $\eta_{3\mu}^M$ have the largest mass difference, so we study their mixing as an example:

$$\eta_{mix}^M = \cos\theta\eta_{1\mu}^M + \sin\theta\eta_{3\mu}^M, \quad (8)$$

where θ is the mixed angle. We calculate its OPE, and find that the resulting spectral density is just:

$$\rho_{mix}^M = \cos^2\theta\rho_{1\mu}^M + \sin^2\theta\rho_{3\mu}^M, \quad (9)$$

The obtained mass is shown in Fig. 4 as functions of θ . When we take $s_0 = 3.5 \text{ GeV}^2$ (solid line), the mass maximum is 2.05 GeV, and the minimum is 1.85 GeV. Therefore, we arrive at the similar result which produces the mass around 2 GeV. We can also consider the mixing of other currents, which would not change the results significantly due to the similarity of single currents. The mass estimates are around 1.8 – 2.1 GeV, where the uncertainty is due to the mixing of two single currents.

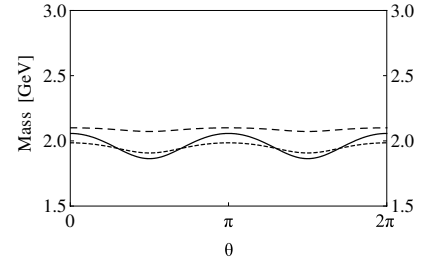


FIG. 4: The mass calculated using the finite energy sum rule, and for the mixed current η_{mix}^M . The curves are obtained by setting $s_0 = 3.5 \text{ GeV}^2$ (solid line), 4 GeV^2 (short-dashed line) and 5 GeV^2 (long-dashed line).

Now let us discuss its decay properties as expected from a naive fall-apart process. As shown in Eqs. (7) the currents contain one $s\bar{s}$ pair. Therefore, we expect that the final states should also contain one $s\bar{s}$ pair. In order to spell out the possible spin of decaying particles and their orbital angular momentum, we need perform a Fierz rearrangement to change $(qq)(\bar{q}\bar{q})$ currents to $(\bar{q}q)(\bar{q}q)$ ones. For illustration, we use one of the four independent $(\bar{q}q)(\bar{q}q)$ currents [9]:

$$\xi_{2\mu}^M = (\bar{s}_a\gamma^\mu\gamma_5 s_a)(\bar{u}_b\gamma_5 u_b) - (\bar{s}_a\gamma_5 s_a)(\bar{u}_b\gamma^\mu\gamma_5 u_b) + \dots \quad (10)$$

All terms of this current have the structure $(\bar{q}_a\gamma^\mu\gamma_5 q_a)(\bar{q}_b\gamma_5 q_b)$. Therefore, the expected decay patterns are: (1) 1^+ and 0^- particles with relative angular momentum $L = 0$, and (2) 0^- and 0^- particles with $L = 1$.

For the S -wave decay, we expect the following two-body decay patterns

$$\sigma_1(I^G J^{PC} = 0^+ 1^{--}) \rightarrow a_1(1260)\eta, a_1\eta', \dots, b_1(1235)\eta, b_1\eta' \dots \quad (11)$$

If we consider, however, the G parity conservation, the first line is forbidden and the second line is the only one allowed. These modes can be observed in the final states $\omega\pi\eta$ and $\omega\pi\eta'$.

For the P -wave decay, we expect (with the G parity conservation):

$$\sigma_1(I^G J^{PC} = 0^+ 1^-) \rightarrow KK, \eta\eta, \eta\eta', \eta'\eta' \dots (12)$$

We can also estimate the (partial) decay width through the comparison with the observed $\pi_1(2015)$ [5], which has $\Gamma_{\text{tot}} \sim 230$ MeV. Assuming that the decay of $\pi_1(2015)$ solely goes through S -wave $b_1\pi$ and that of $\sigma_1(2000)$ through $b_1\eta$, we expect $\Gamma_{\sigma_1 \rightarrow b_1\eta} \sim 160$ MeV, as they are proportional to the S -wave phase space. For the P -wave decay there is an information $\pi_1(2015) \rightarrow \eta'\pi$, which corresponds to $\sigma_1(2000) \rightarrow \eta'\eta$ (Because both $\pi_1(1600)$ and $\pi_1(2015)$ have been observed in the final states $\pi\eta'$ other than $\pi\eta$, we choose $\eta\eta'$ to be the final states of $\sigma_1(2000)$ other than KK and $\eta\eta$). Assuming once again that this is the unique decay mode, we expect that the decay width is approximately 130 MeV. If the decay occurs 50% through $b_1\pi$ ($b_1\eta$) and 50% through $\eta'\pi$ ($\eta'\eta$), we expect that $\Gamma_{\sigma_1} \sim 150$ MeV.

In summary, we have performed the QCD sum rule analysis of the exotic tetraquark states with $I^G J^{PC} = 0^+ 1^-$. We test all possible flavor structures in the

diquark-antidiquark $(qq)(\bar{q}\bar{q})$ construction, $\mathbf{6} \otimes \bar{\mathbf{6}}, \bar{\mathbf{3}} \otimes \mathbf{3}$ and $(\mathbf{3} \otimes \mathbf{6}) \oplus (\mathbf{6} \otimes \mathbf{3})$. We find that only the mixed currents of the flavor structure $(\bar{\mathbf{3}} \otimes \bar{\mathbf{6}}) \oplus (\mathbf{6} \otimes \mathbf{3})$ allow a positive and convergent OPE, and there is only one choice with the quark content $qs\bar{q}\bar{s}$, which have four independent currents. We have then performed both the SVZ sum rule and the finite energy sum rule. The mass estimates are around 1.8 – 2.1 GeV, where the uncertainty is due to the mixing of two single currents. The possible decay modes are S -wave $b_1(1235)\eta$ and $b_1(1235)\eta'$, and P -wave $KK, \eta\eta, \eta\eta'$ and $\eta'\eta'$, etc. The decay width is around 150 MeV through a rough estimation. Here we want to note that we do not know how to determine the mixing angle, which is an interesting problem.

Acknowledgments

H.X.C. is grateful for Monkasho support for his stay at the Research Center for Nuclear Physics where this work was done. This project was supported by the National Natural Science Foundation of China under Grants No. 10625521, 10721063, the Ministry of Education of China, and the Grant for Scientific Research ((C) No. 19540297) from the Ministry of Education, Culture, Science and Technology, Japan.

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